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Research paper

Mathematical modeling of drying behavior of cashew in a solar biomass hybrid dryer

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ABSTRACT

The main objective of this study is to analyze the drying behavior of cashew nut experimentally in a solar biomass hybrid dryer using mathematical models. Suitability of fifteen different mathematical drying models available in the literature is used to describe the drying characteristics of cashew. Experimental data of moisture ratio, temperature and relative humidity obtained from different dryer conditions were fitted to the various empirical drying models. The performance of the drying model was compared based on their correlation co-efficient (R^2), Root Mean Square Error (RMSE) and Reduced Chi-Square (χ^2) between the observed moisture ratios. The two terms and Midilli models showed the best fit under solar drying. Page model was found to be the best model for describing the thin layer drying behavior of cashew for biomass drying and hybrid drying.

1. Introduction

In many agricultural countries, large quantities of food products are dried to improve shelf life, reduce packing costs, lower weights, enhance appearance, encapsulate original flavor and maintain nutritional values [1]. The main goals of drying process in the food industry may be classified in three groups such as, economic considerations, environmental concerns and product quality. Though the primary objective of food drying is preservation, depending on the drying mechanisms, the raw material may end having significant variation in product quality .Cashew nut processing in India is mostly carried out by small farmers in rural areas [2]. Proper drying of cashew kernel enhances good appearance, original taste and maintains nutritional quality. Conventional based dryers are being used by farmers for drying which are energy intensive. In this context, renewable energy based solar biomass hybrid dryer is considered as an alternative to conventional drying to reduce drying cost and environmental sustainability.

Modeling of the drying process is one of the most important aspects of drying technology. The thin layer drying model has been found to be most suitable for characterizing the drying parameters. Several researches on the mathematical modeling and experimental studies had been conducted on the thin layer drying processes of various agricultural products [3–11].

Aghbashla et al. [3] investigated the modeling of thin layer drying behavior of potato slices in a semi industrial continuous band dryer. In order to describe the drying behavior of potato slices, three drying models were fitted to the drying data. The Page model was selected as the best according to R^2, χ^2 and RMSE. The effective diffusivity varied between 3.17×10^{-7} and 15.45×10^{-7} m^2/s, and the energy of activation was found in the range of 39.49–42.34 KJ/mol.

Kavak Akpinar et al. [4] investigated the mathematical modeling of thin layer drying process of long green pepper in solar drying and under open sun drying. The drying data were fitted to thirteen different mathematical models. Among the models, logarithmic model was found to be most suitable model for describing the drying curve of the thin layer forced solar drying process of long green peppers with R^2 of 0.98815, χ^2 of 0.001742354 and RMSE of 0.040998285.

Waewsak et al. [5] investigated a mathematical modeling study of hot air drying for some agricultural products. Biomass dryer was used to dry some agricultural products such as red chili peppers, lemon grass and leech lime leakers. Among the thirteen different models studied, the Midilli model was found to be the best for describing the drying behavior of red chili peppers and leech lime

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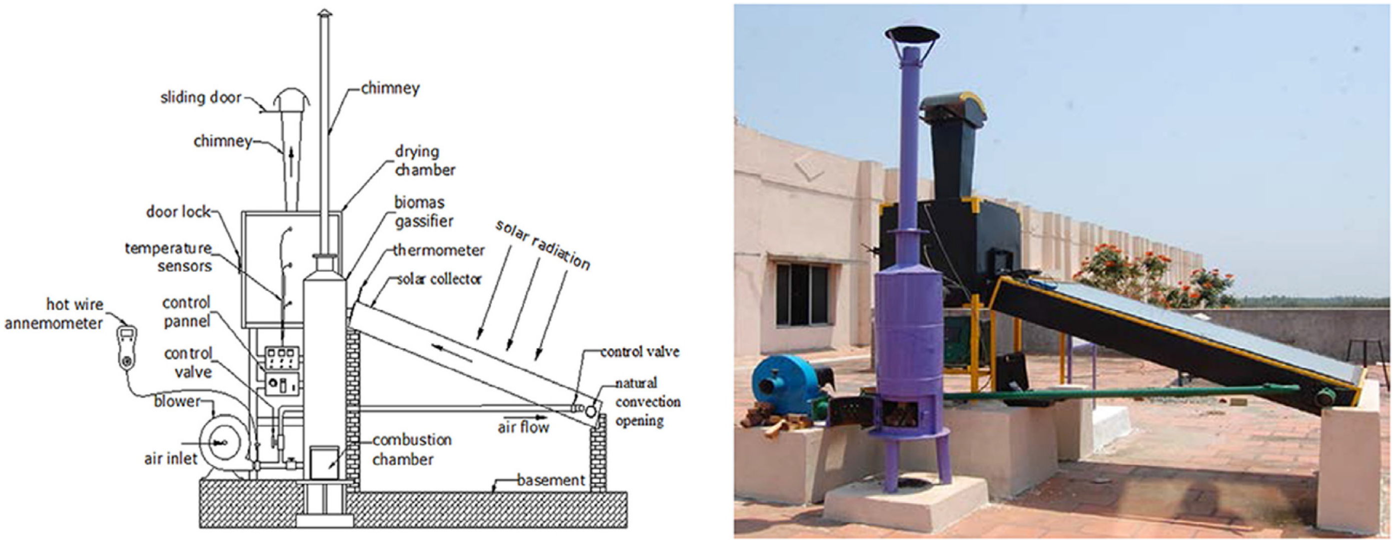

Fig. 1. Schematic and pictorial view of solar biomass hybrid dryer.

Nomenclature

a,b,c	drying constants
exp	experimental
k,g,n	drying constants
k,k_0,k_1	drying velocity constant in drying models
MR	moisture ratio
pre	predicted
P	number of constant
R^2	correlation co-efficient
RH	mean effective relative humidity
RMSE	root mean square error
SEE	standard error of estimate
N	number of observations in drying chamber (%)
T	temperature (°C)
v	air velocity (m/sec)
χ^2	reduced chi-square error
X	moisture content (% db)
X_o	initial moisture content (% db)
X_e	equilibrium moisture content

leaves, where as the Wangh and Singh model was the most suitable for lemon grass.

Hii et al. [6] investigated the thin layer drying model and product quality of cocoa. The drying kinetics and artificial drying process of Cocoa beans were investigated. The dryer was tested with a temperature of 60, 70 and 80°C. The result showed that the new model was best fit for the drying behavior of cocoa beans.

Gunhan et al. [7] studied the mathematical modeling of drying of bay leaves. The experiment was conducted with constant air velocity of 1.5m/sec, relative humidity of 5%, 15% and 25% and different temperatures 40°C, 50°C and 60°C. The drying data were fitted with fifteen different mathematical drying models on the basis of correlation co-efficient (R^2), root mean square error (RMSE), mean bias error (MBE), reduced Chi-square χ^2 and t-statistics method. The result showed that Page model was most suitable for drying of bay leaves.

Zomorodian and Moradi [8] presented mathematical model of forced convection solar drying of Cuminum cyminum using mixed and indirect drying method. Eleven different mathematical models were studied to determine the pertinent coefficients for each model by non-linear regression analysis technique. The best results

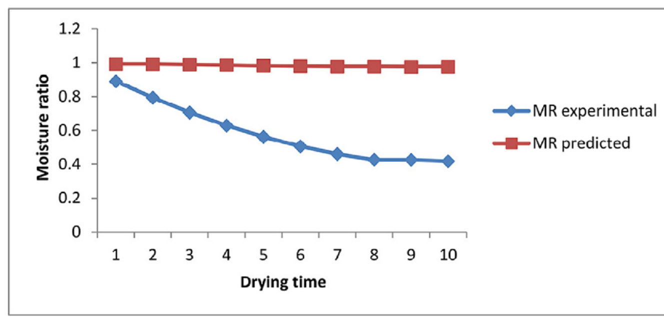

Fig. 2. Variation of MR experimental and MR predicted in solar drying.

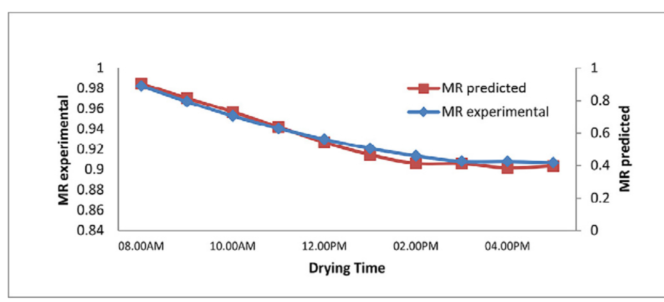

Fig. 3. MR experimental and MR predicted variation in hybrid drying.

were found for the diffusion model with $R^2 = 0.995$, $\chi^2 = 0.0023$ and RMSE = 0.0199 in mixed mode and the Midilli model with $R^2 = 0.995$ $\chi^2 = 0.023$ and RMSE = 0.0225 in indirect mode. And finally the best model was selected due to the high pertinent coefficient.

Kaleta et al. [9] formulated three new types of drying model for drying apple. The drying behavior of apple was investigated in fluidized bed dryer. The three developed models were compared with the accuracy of sixteen models available from the literature. Their accuracies were measured on the basis of correlation co-efficient (R^2), root mean square error (RMSE), and reduced chi-square (χ^2). At the end of this study, the Page model and one of the empirical models formulated by the author were considered as the most suitable model with $R^2 > 0.9977$, RMSE = 0.0094–0.0167, $\chi^2 = 0.0001$–0.0002.

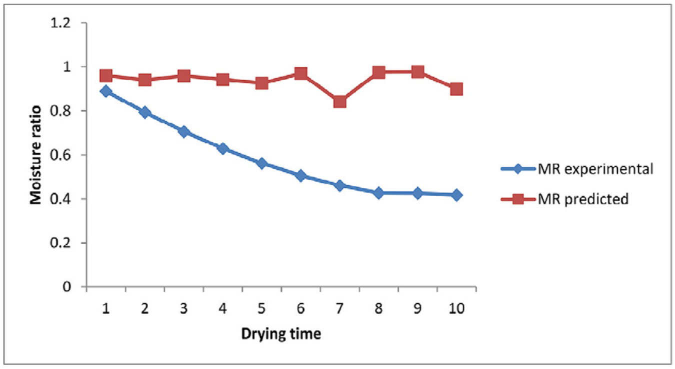

Fig. 4. MR experimental and MR predicted variation in biomass drying.

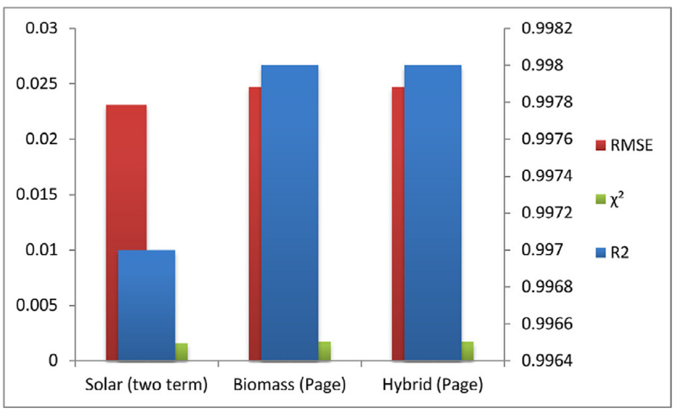

Fig. 5. Average value of R^2, χ^2 and RMSE.

Kumar et al. [10] performed the mathematical modeling of thin layer hot air drying carrot Pomace. The experiments were carried out at 60, 65, 70 and 75°C at an air velocity of 0.7m/sec. The average value of effective diffusivity ranged from 2.74×10^{-9} to 4.64×10^{-9} m^2/sec and the activation energy value was 23.05 KJ/mole for drying of carrot Pomace. With increase of temperature, the drying time of the carrot Pomace decreased where as the effective diffusivity increased with increasing drying temperature.

Basunia and Rabbani investigated the best fitted thin-layer rewetting model for medium – grain rough rice. Around five models, diffusion, page, exponential, and polynomial were compared with experimental data on the basis of standard error of estimate (SEE). The comparison showed that the diffusion and page models had almost the same strength of fit with the average SEE value which was less than 0.0015 [11].

From the vast extensive literature review, very scarce information is available on thin layer drying behavior of cashew kernel. Hence, this study was carried out to fulfill the existing research gaps on thin layer modeling of cashew kernel.

The main objectives of this study are to:

- Investigate drying kinetics of cashew kernel in a solar biomass hybrid dryer.
- Study the most suitable drying models for describing the drying behavior of cashew.
- Find out the size of drying equipment and drying chamber based on the operating condition of the dryer.

Table 1
Uncertainties of the various parameters.

Parameters	Expression	Unit	Value
Ambient air temperature	T	°C	±0.2
Collector outlet temperature	T	°C	±0.4
Drying chamber bottom tray temperature	T	°C	±0.35
Drying chamber middle tray temperature	T	°C	±0.38
Drying chamber top tray temperature	T	°C	±0.25
Solar intensity	I	W/m^2	±1
Ambient relative humidity	RH	%	±2
Drying chamber relative humidity	RH	%	±1.5
Weight loss of the sample	m	g	±0.002
Air velocity	V	m/sec	±0.1

2. Materials and methods

2.1. Materials

For the purpose of sample preparation, 80 kg of boiled cashew nut shell was procured from a local farmer in Cuddalore district, Tamil Nadu, India. The outer shell is removed by using hand operated cutter to obtain raw cashew kernel with initial moisture content of 10%. For conducting drying experiments, 40 kg of cashew kernel was loaded in the ten drying trays with 4 kg in each tray. The experiment was conducted from 8:00 am to 5:00 pm in solar mode, biomass mode and hybrid mode.

2.2. Drying equipment

Schematic diagram of solar biomass hybrid dryer is shown in Fig. 1 . It consist of a solar collector, drying chamber, biomass backup heater and blower with variable speed control unit [12,13].

2.3. Experimental uncertainty

Based on instruments selection, environmental condition, calibration, observation, test planning, certain errors and uncertainties occur during measurements [14]. During the drying experiment of cashew kernel, the temperature, solar intensity, relative humidity and weight losses were measured with appropriate instruments. The uncertainties of measurements are presented in Table 1.

2.4. Modeling of thin layer drying curves – theoretical approach

For investigating the drying characteristics of cashew kernel, it is important to model the drying behavior effectively. The moisture ratio (MR) is defined as $MR = (X-X_e)/(X_0-X_e)$ [15]. The values of X_e are relatively small compared to X or X_e for the drying time, thus the MR can be simplified to $MR = X/X_0$. Accurately modeling the drying behavior of cashew kernels is very important for studying drying kinetics. In this study, the experimental thin layer drying data of cashew kernel were fitted into 15 commonly used mathematical drying models [16] listed in Table 2.

2.5. Statistical analysis

To validate the goodness of the fit, three statistical criteria, namely root of mean square error (RMSE), reduced chi square (χ^2) and coefficient of determination (R^2) were calculated using MS excel computer program. The coefficient of determination (R^2) is one of the primary criteria in order to evaluate the fit quality of selected models. In addition to R^2 , reduced chi-square (χ^2) and root mean square error (*RMSE*) are used to determine suitability of the

Table 2
Thin Layer Drying Mathematical models.

No	Model	Model equation	References
1	Lewis	MR = exp(-kt)	Lewis (1921)
2	Page	MR = exp(-kt^n)	Page (1949)
3	Modified page	MR = exp[(-kt^n)]	Overhults et al. (1973)
4	Henderson and Pabis	MR = a exp(-kt)	Westerman (1973)
5	Logarithmic	MR = a exp(-kt) + c	Togrul and Pehlivan (2003)
6	Two-term	MR = a exp(-k_0t) + b exp(k_1t)	Henderson (1974)
7	Two-term exponential	MR = a exp(-kt) + (1-a)exp(-kat)	Sharaf-Elden et al. (1980)
8	Wangh and Singh	MR = 1 + at + bt^2	Wangh and Singh (1978)
9	Diffusion approach	MR = a exp(-kt) + (1-a)exp(-kbt)	Demir et al. (2007)
10	Verma et al.	MR = a exp(-kx)(1-a)exp(-gx)	Verma et al. (1985)
11	Modified Henderson and Pabis	MR = a exp(-kt) + b exp(-gt) + c exp(-ht)	Karathanos (1999)
12	Simplified Fick's diffusion equation	MR = a exp(-k(t/L^2))	Diamente and Munro (1991)
13	Midilli et al.	MR = a exp(-kt^n) + bt	Midlli et al. (2002)
14	Demir et al.	MR = a exp(-kt^n) + b	Demir et al. (2007)
15	Weibull	MR = exp(-(t/a)^b)	Corzo et al. (2008)

fit [17,18]. For the best fit, the R^2 value should be high and *RMSE* values should be low. This can be calculated as follows:

$$\mathrm{RMSE} = \sqrt{\left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2\right]} \quad (1)$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(\mathrm{MR}_{\mathrm{exp,i}} - \mathrm{MR}_{\mathrm{pre,i}}\right)^2}{\mathrm{N-p}} \quad (2)$$

$$\mathrm{R}^2 = \frac{\left[\sum_{i=1}^{N}\left(MR_{exp,i} - \overline{MR_{exp}}\right)\left(MR_{pre,i} - \overline{MR_{pre}}\right)\right]^2}{\sum_{i=1}^{N}\left(MR_{exp,i} - \overline{MR_{pre}}\right)^2 \sum_{i=1}^{N}\left(MR_{pre,i} - \overline{MR_{pre}}\right)^2} \quad (3)$$

3. Results and discussion

The reliability of the best model for describing the thin layer drying curves of the Cashew kernels was evaluated by comparing the predicted moisture ratio with experimentally observed moisture ratio in the solar biomass hybrid dryer.

3.1. Variation of MR experimental and MR predicted with drying time for forced solar drying

The variation of moisture ratio of the cashew kernel with time for forced solar drying is shown in Fig. 2 . The experimental moisture ratio was reduced from 0.9 to 0.4.The predicted moisture ratio values varied from 1 to 0.98.

3.2. Variation of MR experimental and MR predicted with drying time for hybrid drying

The variation of MR predicted and experimental values in hybrid drying are plotted in Fig. 3 . The result showed that if the drying time increases, moisture ratio will be decreased. The experimental moisture ratio decreased from 0.98 to 0.9 and the predicted moisture ratio decreased from 0.98 to 0.4.

3.3. Variation of MR experimental and MR predicted with drying time for biomass drying

The predicted and experimental value of moisture ratio in biomass drying is shown in Fig. 4 . The result showed that if the drying time increases, moisture ratio will be decreased. The experimental moisture ratio decreased from 0.98 to 0.9 and the predicted moisture ratio decreased from 0.9 to 0.5.

3.4. Mathematical modeling of thin layer drying

3.4.1. Statistical results of thin layer drying models for hybrid dryer

By carrying out the multiple regression analysis using moisture ratio, temperature and relative humidity, the outcome of the accepted model constants and coefficients were listed in Table 3. The coefficient of determination (R^2), chi-square (χ^2) and root mean square error (RMSE) were used to evaluate the models. It is assumed that the model that has the highest R^2 and the lowest χ^2 and RMSE is the best suited one. The results of the statistical analysis for the eleven models were presented in Table 3. From these results, the Page model was found to be the best, followed by the logarithmic model. The value of R^2 of the Page model was 0.998, indicating good fit and *RMSE* were also good (0.0247) indicating the suitability of the fit.

3.4.2. Statistical results of thin layer drying models for solar drying

The results obtained by regression analysis for forced solar drying are listed in Table 4. The result shows the obtained value of model coefficients and the values of R^2, χ^2 and RMSE. Among the above 11 models, two terms gave the best result.

3.4.3. Statistical results of thin layer drying models for biomass drying

Experimental moisture ratios obtained from the biomass drying were fitted to the selected thin layer drying model. By using regression analysis, the value of correlation coefficient (R^2), the reduced chi-square (χ^2) and Root Mean Square Errors (RMSE) and their coefficients are determined and listed in Table 5. The highest R^2 value and lowest values of χ^2 and RMSE were obtained in Page model. Page model can be selected as a suitable model to predict the drying characteristics of cashew in biomass drying.

Table 3
Statistical result of thin layer drying models for hybrid drying.

Model name	Model coefficients	R^2	RMSE	χ^2
Lewis	K = 0.030214	0.916	0.0773	0.0313
Page	K = 0.28496, n = 0.455996	0.998	0.0247	0.0017
Modified page	K = 0.0812, n = 0.3205	0.943	0.0712	0.0032
Henderson and Pabis	a = 0.06149, K = 0.023	0.911	0.0921	0.0046
Logarithmic	a = 0.761761, K = 0.0921	0.972	0.0638	0.0082
Two term	a = 0.00312, b = 0.2813, k1 = 0.143, k0a = 1.273	0.933	0.0376	0.0041
Exponential two term	a = 0.0179, k = 0.111	0.920	0.0375	0.1060
Wang and Singh	a = 1.00032, b = 0.7932	0.873	0.0316	0.0238
Thompson	a = 0.000944, b = 0.1932	0.911	0.0855	0.0412
Diffusion Approximation	a = 0.45651, K = 0.0310, b = 0.04732	0.891	0.0332	0.0132
Midilli et al.	a = 1.1143, K = 0.1791, n = 1.3215, b = 0.00321	0.923	0.872	0.0712

Table 4
Statistical result of thin layer drying models for solar drying.

Model name	Model coefficients	R^2	RMSE	χ^2
Newton	K = 0.13241	0.847	0.1028	0.0100
Page	K = 0.2779154, n = 0.048795	0.891	0.0266	0.0033
Modified page	K = 0.68921, n = 0.2115	0.942	0.2204	0.0271
Henderson and Pabis	a = 0.924798, K = 0.418	0.931	0.0249	0.0036
Logarithmic	a = 0.083952, K = 0.0032145	0.945	0.0638	0.0032
Two term	a = 0.049, b = 0.47008, k_1 = 0.085, k_0a = 0.465214	0.997	0.0231	0.0016
Exponential two term	a = 0.411528, k = 0.189254	0.960	0.0792	0.0194
Wang and Singh	a = −0.03257, b = 0.008524	0.916	0.1329	0.0258
Thompson	a = 0.00497, b = 0.3915	0.925	0.0324	0.0177
Diffusion Approximation	a = 0.56132, K = 0.0121, b = 0.007895	0.932	0.0299	0.0029
Midilli et al.	a = 1.37457, K = 0.1254, n = 0.5698, b = 0.0258	0.977	0.0243	0.0071

Table 5
Statistical results of thin layer drying models for biomass drying.

Model name	Model coefficients	R^2	RMSE	χ^2
Newton	K = 0.054023	0.923	0.0827	0.0413
Page	K = 0.28496, n = 0.455996	0.997	0.0234	0.0016
Modified page	K = 0.0681, n = 0.5203	0.962	0.0676	0.0028
Henderson and Pabis	a = 0.941654, K = 0.049	0.932	0.0921	0.0346
Logarithmic	a = 0.839717, K = 0.095284	0.978	0.0617	0.0074
Two term	a = 0.049, b = 0.470827, k_1 = 0.049, k_0a = 0.470827	0.945	0.0776	0.0024
Exponential two term	a = 0.259568, k = 0.149879	0.972	0.0675	0.1060
Wang and Singh	a = −0.03146, b = 0.000253	0.863	0.0516	0.0283
Thompson	a = 0.003778, b = 0.392219	0.923	0.0955	0.0314
Diffusion Approximation	a = 0.766617, K = 0.11179, b = 0.053014	0.871	0.0432	0.0245
Midilli et al.	a = 1.000377, K = 0.174944, n = 0.657723, b = 0.00125	0.943	0.0772	0.1712

3.4.4. Average value of r^2, χ^2 and RMSE for solar biomass hybrid dryer

The model with the maximum R^2 and minimum $\chi 2$ and RMSE value among all the three modes of operation of the dryer is finally chosen. The average value of R^2, χ^2 and RMSE for the best models with highest coefficient of determination (R^2) for various modes of drying is shown in Fig. 5 . The higher R^2 value and the lower χ^2 value and RMSE value, the better is the goodness of fit. The values agreed well with values obtained by other researchers [4–11].

4. Conclusion

In this study, the drying behavior of cashew kernel in various modes of drying (solar drying, biomass drying and hybrid drying) have been reported. In order to describe the drying behavior of cashew kernel, eleven thin layer drying mathematical models were fitted to the drying data obtained from solar biomass hybrid dryer. Mathematical models were further validated by comparing the predicted moisture ratio against the experimental moisture based on correlation co-efficient, reduced chi-square value and root mean square error value. Two term model showed the best curve fitting for the experimental moisture ratio value for the forced solar dryer. Page model showed good fit for biomass and hybrid drying. It may be concluded that the fitted drying model adequately explained the drying behavior of the cashew kernel. The suggested solar biomass hybrid dryer can be redesigned further based on the mathematical model to enhance the drying process. It will also be helpful in obtaining an optimum moisture level for high quality cashew kernel production.

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